Medio-lateral Knee Fluency In ACL-Injured Athletes During Dynamic Movement Trials

Undergraduate Honors Thesis

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By

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Abstract

Correction of lower-extremity neuromuscular impairments after anterior cruciate ligament (ACL) injury is vital to rehabilitation and successful return to sport. Frontal plane knee control during the landing phase of dynamic movements is a common measure of lower-extremity neuromuscular control. Limb asymmetries may indicate knee control deficits or incomplete recovery from injury, which can predispose injured athletes to additional knee injury and associated morbidities (24, 36). Therefore, the purpose of this study was to determine the effects of ACL injury on bilateral knee biomechanics during dynamic movement tests. This study utilized two-dimensional (2D) frontal plane video as a more spatially, financially, and clinically translatable alternative to three-dimensional motion capture technology. 2D frontal plane video of single leg drop (SLD), cross over drop (COD), and drop vertical jump (DVJ) dynamic movement trials were analyzed for eleven ACL-injured athletes (21.1±12.9 years; 2 male, 9 female). Intersecting vertical and horizontal lines, generated in ImageJ software, were used to define and track the knee joint center for 500 milliseconds after landing. Knee velocity was calculated from positional values and analyzed in MATLAB to determine normal fluency (F_N), defined as the number of times per second knee velocity changed direction. The inverse of this calculation, analytical fluency (F_A), was used to associate larger numerical values to more fluent movement. F_A for involved limbs was significantly lower than uninvolved limbs for SLD trials ($p<0.001$) but not for COD ($p=0.788$) or DVJ trials (p=0.136). Furthermore, a relationship for the involved limb was established for F_A such that: SLD < COD < DVJ. A significant asymmetry in the medio-lateral range of the knee joint center position was observed in SLD trials (p=0.003) with a trend towards a similar asymmetry in COD (p=0.0596) but not DVJ trials (p=0.1575). Decreased F_A of involved limbs, indicative of knee control deficits, is consistent with previous studies. Asymmetries in the medio-lateral range of the knee joint center may indicate adverse landing strategies in the involved limb. Furthermore, modeling the medio-lateral knee velocity during landing as a damped harmonic oscillator, knee fluency may be related to Euclidean jolt, a descriptor of the rate-of-change of force. Analytical relationships between limbs suggest greater jolt for involved than uninvolved limbs in SLD trials. Jolt, implicated in musculoskeletal injury, serves to further contextualize, and mathematically support, the clinical relevance of knee fluency. Elucidation of landing strategies and force dissipation, quantified by fluency and jolt, in healthy limbs could provide new approaches for ACL-injury rehabilitation and endpoint determinations.

Dedication

This thesis is dedicated to my dad who supports and encourages me in everything that I do and who has endowed me with a great passion for and appreciation of research.

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Panos, J.A., Han, L., Rankin, S., Zorn, A.M. *Characterization of the Expression Pattern of the Transcription Factor Osr1 During Early Foregut Development in the Mouse.* Poster presented at the 2014 Summer Undergraduate Research Fellowship Poster Symposium, Cincinnati Children's Hospital, Cincinnati OH. August 7, 2014.

Panos, J.A., Wordeman, S.C., Hewett, T.E. *Effects of Neuromuscular Training on Strength and Functional Symmetry in ACL-Injured and Uninjured Athletes.* Poster presented at 2014 Denman Undergraduate Research Forum, The Ohio State University, Columbus, OH. March 26 2014.

Panos, J.A., Sitaraman, S., Martin, E., Weaver, T. *Normal Pulmonary Histopathology in the* SOD^{G93A} *Transgenic Mouse is Associated with Reduced Levels of BiP.* Poster presented at 2015 Summer Undergraduate Research Fellowship Poster Symposium, Cincinnati Children's Hospital, Cincinnati OH. August 1, 2015.

Panos, J.A., Hoffman, J., Wordeman, S.C., Hewett, T.E. *Medio-lateral Knee Fluency in ACL-Injured Athletes During Dynamic Movement Trials.* Poster presented at 2015 Denman Undergraduate Research Forum, The Ohio State University, Columbus, OH. March 25 2015.

Fields of Study

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Minor Field: Minor

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INTRODUCTION

Following an anterior cruciate ligament (ACL) rupture, athletes may experience substantial physical, psychological, and financial stresses in returning to previous levels of activity. Surgical ACL reconstruction (ACLR) is the primary treatment to restore knee stability after injury, and is usually required to return to high levels of activity (19). Approximately 250,000 ACL reconstruction (ACLR) surgeries are performed annually in the United States (20). After surgery, only 63% of professional football players return to play, and they require on average 10.8 months of rehabilitation (21). Long-term financial costs of ACL injury can range from $38,121 for surgical reconstruction to $88,538 for rehabilitation (22). ACL injury and timing of ACLR surgery can have pervasive psychosocial effects on collegiate athletes including adverse academic consequences such as missed class time and the loss of athletic scholarships (23).

Those who suffer primary ACL injury and undergo ACLR surgery are at significant risk to suffer a second ACL injury (24). Strength and functional limb asymmetries are indicative of risk for primary ACL injury in healthy athletes and persist after ACL reconstruction (25, 26, 27, 28, 29, 30). Furthermore, poor neuromuscular control is associated with both primary (3, 31, 32, 33) and secondary ACL injury (29, 34). Medio-lateral knee displacement is an important measure of neuromuscular control that is frequently assessed in individuals at risk for ACL injury and during the rehabilitation of ACL-injured patients (1). Knee fluency is a recently introduced evaluation that incorporates time-dependent measurements of medio-lateral knee displacement and neuromuscular control during the landing portion of dynamic movement tasks (1). Originally, fluency was demonstrated to vary between control, ACLR individuals, and conservatively treated, non-ACLR subjects. The observed differences in fluency between the limbs of healthy and injured individuals across multiple treatment groups was identified as a marker of the incomplete reestablishment of healthy landing strategies for ACL-injured individuals (1). In this manner, fluency can also serve as a biomechanical parameter to assess the progression of ACL-injured athletes through rehabilitation programs designed to restore limb function to native or pre-injury levels.

To assess biomechanical descriptors, such as medio-lateral knee displacement or fluency, that have the potential to augment ACL injury risk among athletes, a variety of clinical dynamic movement tests may be used (2, 3, 4). The drop vertical jump (DVJ) is a biphasic-landing task in which an individual drops from a stationary platform, lands on both feet, rebounds to a maximal vertical jump, and recovers with a two foot landing (5). Based upon evidence that implicates single leg landings and directional changes as the most frequent contributor to the ACL injury mechanism, increased attention has been devoted to unilateral clinical tests, such as the single leg drop (SLD) and the crossover drop (COD) (6, 7, 8). To perform the SLD, an athlete balances on a single leg, drops from a stationary platform, and lands on the same limb. Similarly, to complete a COD, the subject jumps laterally from an elevated platform off one leg and lands on the contralateral limb in a balanced ground position. Both the SLD and the COD imitate the forces of rapid deceleration borne by the lower extremities during stability and agility maneuvers performed by athletes during competition.

Three-dimensional (3D) motion analysis technologies effectively and reliably measure lower limb positioning during clinical dynamic movement trials (9, 10, 11, 12). However, a two-dimensional (2D) frontal plane approach that uses a standard video camera offsets the significant financial and spatial requirements of a 3D system (10, 13, 14). McLean et al. (2005) validated the utilization of a 2D camera to characterize frontal plane knee motion for dynamic movement trials in which the knee joint center is readily recognized (15). The reliability of 2D video analyses for the measurement of frontal plane knee valgus during the DVJ and single leg dynamic movement tests was further demonstrated by Munro et al. (2012).

Based upon these prior investigations, we sought to determine the effects of ACL injury on bilateral knee biomechanics during SLD, COD, and DVJ dynamic movement trials using 2D frontal plane video analyses. We hypothesized that:

(1) Knee fluency will be decreased for involved limbs and may be accompanied by increased medial knee displacement for SLD and COD trials, but not for DVJ tests.

(2) Knee fluency values will follow the general trend: COD < SLD < DVJ for both involved and uninvolved limbs.

METHODS

Eleven ACL-injured athletes (N=11; Males N=2, Age: 26.0±5.7 years, Height: 188.3±6.7 cm, Weight: 101.2±27.6 kg; Females N=9 Age: 19.9±14.0 years, Height: 164.6±4.4 cm, Weight 61.9±8.3 kg) participated in a series of dynamic movement tests. 2D frontal plane video for 125 SLD trials, 137 COD trials, and 60 bilateral DVJ trials were obtained. All video clips were processed in GoPro Studio software (GoPro Inc., San Mateo, California) to remove fish-eye distortion. ImageJ software (ImageJ, National Institutes of Health, Bethesda, Marlyand) was used to determine definitive landing time points and track the position of the knee joint center throughout the landing phase for each video clip. For each image within a clip stack, positional values based on pixel elements were discretely defined as constituents of a 2D Euclidean space within ImageJ. The z-position of an image within the clip stack was defined in accordance with the frame rate of the GoPro camera. In this manner, the ImageJ video analysis software precisely assessed spatial and temporal knee motion in the 2D frontal plane.

The position of the toe was first identified and defined in multiple images before and after visual estimation of landing. Definitive landing was described as the first image within a clip stack after which no appreciable vertical position change of the toe occurred. The landing phase of a dynamic movement task was defined as 500 milliseconds after definitive landing. Using the GoPro frames per second rate of 59.94, the entirety of the landing phase of the trial was defined using discrete image numbers within a clip stack.

After the identification of the landing image in a stack, the knee joint center was identified and tracked throughout the z-position images comprising the landing phase. A vertical line, guided by a retro-reflective marker placed on the skin near the tibial tuberosity, was drawn in ImageJ to intersect with a horizontal line, guided by markers placed on the skin near medial and lateral epicondyles of the knee, for each image within the landing phase portion of a clip stack. The intersection of the two lines, defined as the knee joint center, was calculated in MATLAB using the endpoints of the vertical and horizontal lines. Medio-lateral positional values were used to measure knee joint center displacements. Medial and lateral displacement values were defined as the absolute difference between the maximum medial or lateral knee position and the knee joint center position at landing, respectively. The medio-lateral range of the knee joint center was defined as the absolute difference between the maximum medial and lateral displacement of the knee during the landing phase of a dynamic movement trials. Knee displacement parameters were compared between involved and uninvolved limbs across SLD, COD, and DVJ dynamic movement trials.

As an integral component of fluency and displacement calculations, 2D frontal plane knee velocities were tabulated from medio-lateral positional values and analyzed for involved and uninvolved limbs across SLD, COD, and DVJ trials. The distance per pixel for a given image, was determined to be 0.606 centimeters. Using the GoPro frame rate as an indicator of the z-position, time differences between images in a clip stack, and pixel-distance values, the raw medio-lateral knee velocity data were converted to meter per second velocity values. For the purpose of this study, the average medio-lateral velocity of the knee throughout a single dynamic movement trial was determined.

Raw knee velocities were plotted as a function of time to determine fluency. Velocities less than 10% of the absolute maximum were filtered from the data set as an artifact of 2D video analysis. A polynomial, generated in MATLAB, was fitted to the velocity versus time graph. The real, unique roots of the polynomial were depicted graphically, and visually confirmed to determine fluent events. A fluent event, denoted by a root of the polynomial, was defined as the point at which the medio-lateral velocity of the knee changed direction in the 2D frontal plane. Knee fluency was calculated as the number of fluent events per unit time and defined as normal fluency or F_N. For statistical analyses, the inverse of F_N was used such that larger values indicated greater fluency; this value was defined as analytical fluency or F_A.

STATISTICAL METHODS

Medio-lateral knee range, F_A, and velocity values were compared between involved and uninvolved limbs using a paired two-sample *t*-test. One-way Analysis of Variance (ANOVA) testing was used to compare F_A values between SLD, COD, and DVJ trials for involved and uninvolved limbs. Post-hoc paired two-sample *t*-tests were performed to further delineate F_A relationships for dynamic movement trials grouped by involved and uninvolved limb status. An alpha value of 0.05 was used for all statistical tests of significance. All numerical values are displayed as mean ± standard deviation.

RESULTS

Medio-lateral Knee Displacement

The medio-lateral range of the knee joint center movement during SLD trials was 8.46±2.84 pixels for involved limbs and 10.33±3.69 pixels for uninvolved limbs ($p=0.003$). Similarly, the knee joint center range for COD trials was 16.19±4.10 pixels for involved limbs and 17.84±5.33 pixels for uninvolved limbs ($p=0.0596$); for DVJ trials, the medio-lateral range of the involved limb was 8.99±3.06 pixels, while the range of the uninvolved limb 10.14±3.19 pixels ($p=0.1575$). (Figure 1)

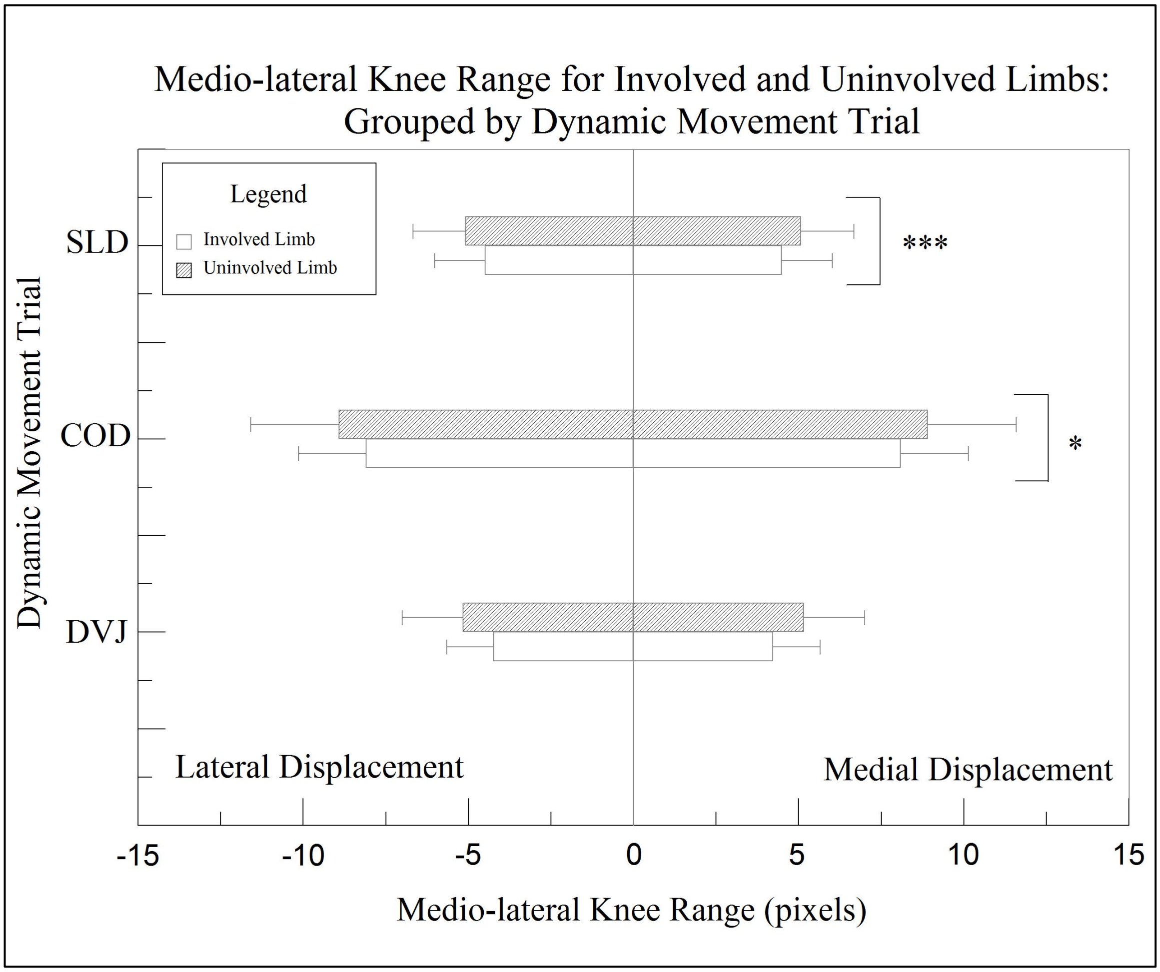

Figure 1. Medio-lateral Knee Movement Range for Involved and Uninvolved Limbs

There was no difference in the maximum medial knee displacement during landing between involved and uninvolved limbs for SLD, 4.67±4.17 and 6.20±5.30 pixels (p=0.0967); COD, 15.89±4.41 and 17.17±6.20 pixels (p=0.1932), or DVJ trials 3.20±3.25 and 3.91±3.67 pixels (p=0.2655). (Figure 2)

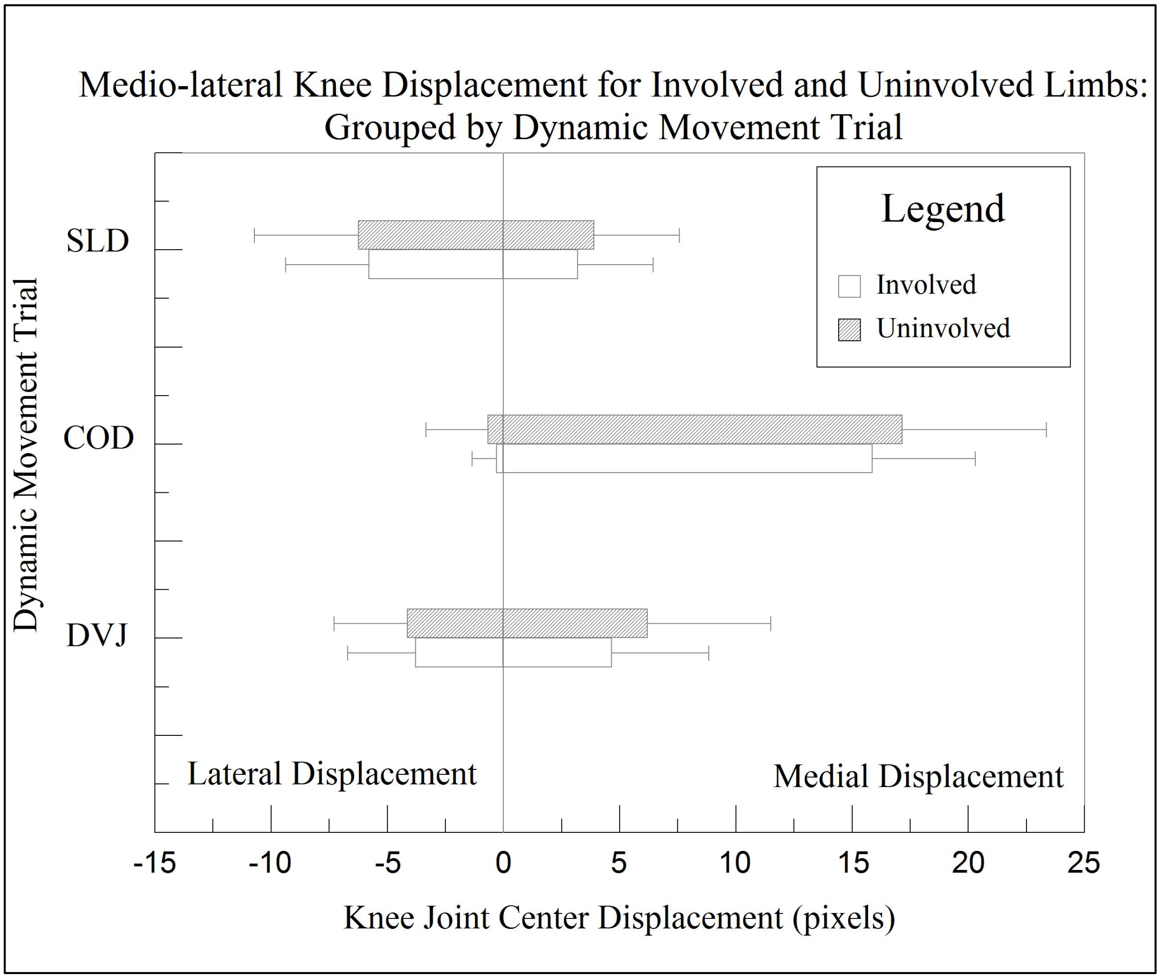

Figure 2. Medio-lateral Knee Displacement for Involved and Uninvolved Limbs

Knee Fluency

F_A values for involved and uninvolved limbs were 0.1275±0.0507 seconds and 0.1833±0.0981 sec for SLD trials, respectively, 0.1742±0.0808 sec and 0.1755±0.0814 sec for COD trials, respectively, and 0.214±0.123 sec and 0.248±0.124 sec for DVJ trials, respectively. (Figure 3)

Two-sample paired *t*-tests for differences in F_A between involved and uninvolved limbs revealed significance for SLD trials ($p<0.001$), but not COD or DVJ tests (COD: $p=0.788$; DVJ: $p=0.136$). (Figure 3)

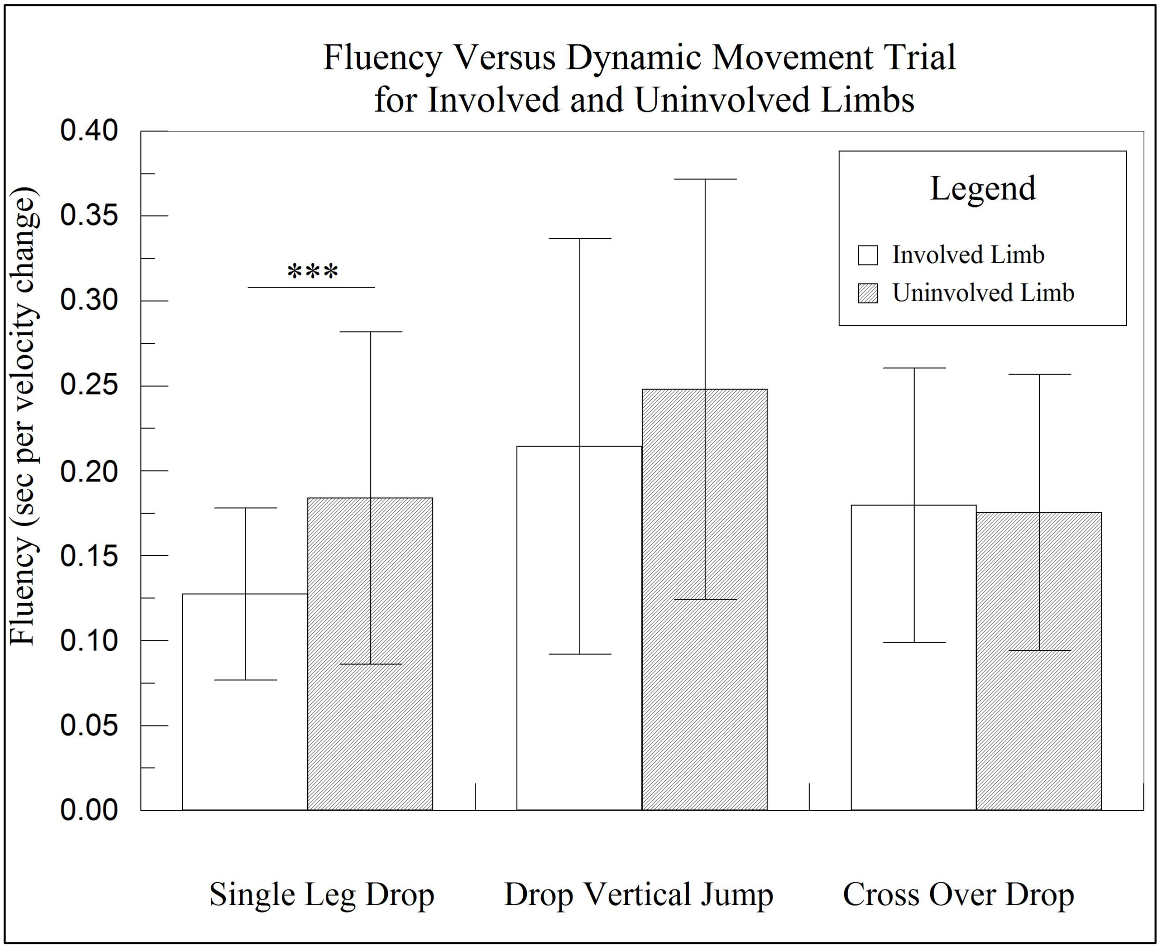

Figure 3. Fluency for Involved and Uninvolved Limbs

F_A values for involved and uninvolved limbs differed between SLD, COD, and DVJ trials (involved: $p<0.001$; uninvolved: $p<0.001$). (Figure 4) Post-hoc *t*-tests were conducted between trials for involved and uninvolved F_A data. For the uninvolved limb, knee F_A differed between DVJ versus SLD trials ($p=0.0017$) and DVJ versus COD trials (p<0.001). (Figure 4) Knee F_A values for SLD versus COD trials were not different for the uninvolved limb (p=0.6491). Similar relationships in knee F_A between DVJ versus SLD trials (p<0.001) and DVJ versus COD trials (p=0.0358) were demonstrated for the involved limb. Importantly, the involved limb F_A values differed between SLD and COD trials (p<0.001), establishing the relationship for the involved limb of: SLD < COD < DVJ. (Figure 4)

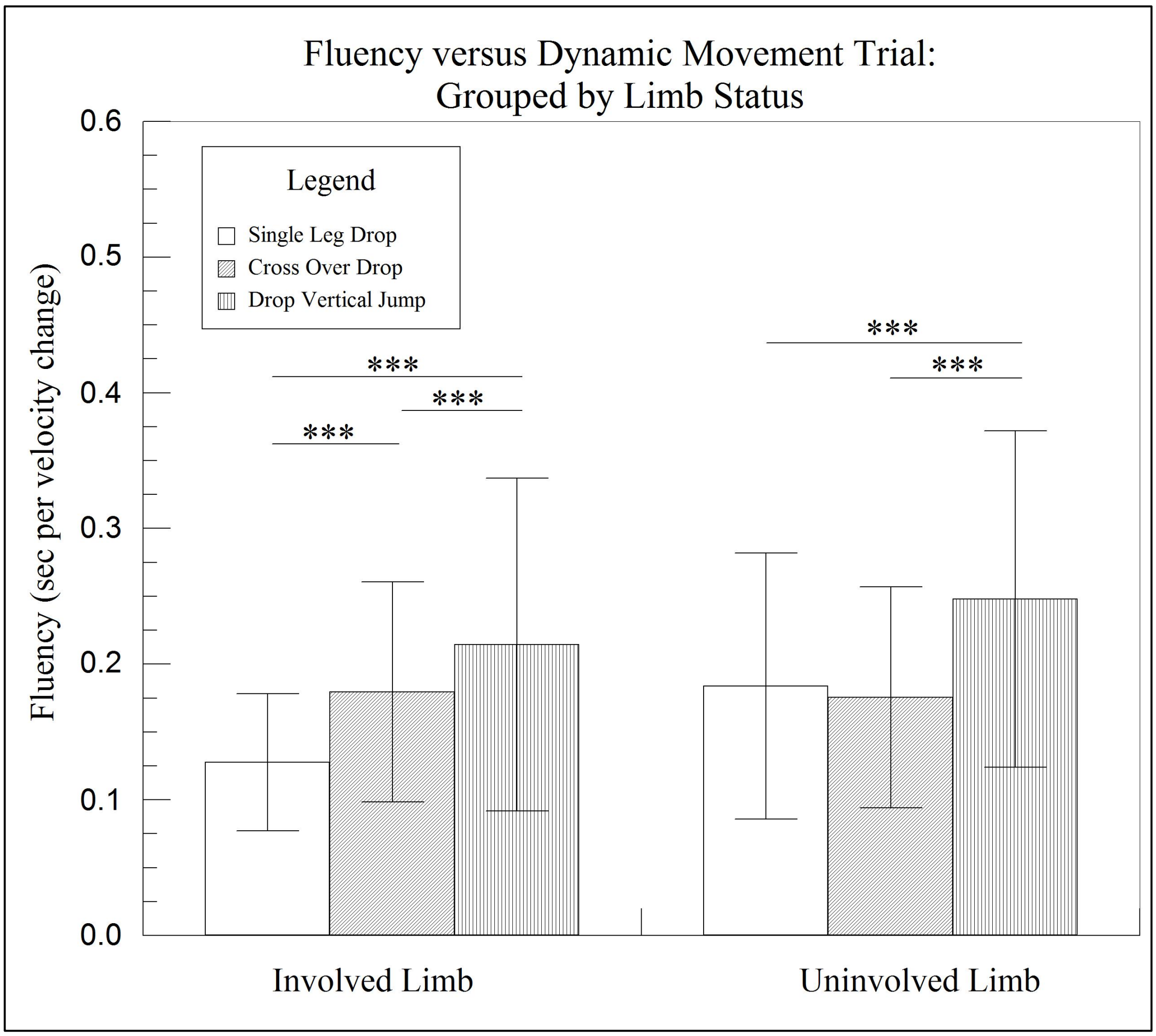

Figure 4. Involved and Uninvolved Limb Fluency

Medio-lateral Knee Velocity

The average 2D frontal plane knee velocity for involved limbs was observed to be 0.3392±0.0014 m/s, 0.4581±0.0017 m/s, and 0.2921±0.0012 m/s for SLD, COD, and DVJ trials, respectively. Medio-lateral knee velocity averages for uninvolved limbs were 0.3398±0.0014 m/s, 0.4787±0.0019 m/s, and 0.2825±0.0011 m/s for SLD, COD, and DVJ trials, respectively. Asymmetries in the medio-lateral velocity of the knee throughout the landing phase were not observed between involved and uninvolved limbs for SLD (p=0.9641), COD (p=0.2996), or DVJ (p=0.4531) dynamic movement tests. (Table 1)

Table 1. Medio-lateral Knee Velocities

Average Knee Velocity (m/s)	Involved Limb	Uninvolved Limb	p value
SLD	0.3392±0.0014	0.3398±0.0014	0.9641
COD	0.4581±0.0017	0.4787±0.0019	0.2996
DVJ	0.2921±0.0012	0.2825±0.0011	0.4531

DISCUSSION

Limitations

Although almost 400 individual data points were obtained from over 300 dynamic movement trials, this study examined a relatively small cohort (N=11), with a notable gender imbalance (male: N=2; female: N=9). Furthermore, toe angulation during landing followed by the natural flexion of the knee could produce knee displacement in the medial or lateral 2D frontal plane as a result of regular landing strategies as opposed to biomechanically-unhealthy movement quantified by diminished fluency or increased medial knee displacement values. Although the effects of toe angulation were not thought to significantly alter the findings of this study, further analyses should be performed using 3D motion capture software to corroborate and expand upon the observed results.

This study measured 2D frontal plane knee movement in ACL-injured athletes during the landing phase of multiple dynamic movement trials between involved and uninvolved limbs. Knee F_A was significantly decreased for involved limbs in SLD trials compared with uninvolved limbs and demonstrated a stepwise trend between dynamic movement trials for involved limbs such that: SLD < COD < DVJ. Knee F_A for injured and healthy limbs measured initially by Roos et al. in 2014 for single leg hop trials was comparable to the fluency values recorded by our group in SLD trials (Roos: Involved:

0.14±0.34 sec, Uninvolved: 0.17±0.41 sec, Panos: Involved: 0.1275±0.0507 sec, Uninvolved: 0.1833±0.0981 sec).

Our results demonstrate that landing phase knee stability, as quantified by F_A, is significantly greater for bilateral compared to unilateral tasks (DVJ vs. SLD or COD) for both involved and uninvolved limbs. Yet, it is interesting to examine the trends between clinical dynamic movement tests, especially for a single limb. Differences in knee F_A between SLD and COD trials were significant for involved limbs, but not for uninvolved limbs. Furthermore, while the SLD trial displayed the only significant difference in F_A when compared directly between involved and uninvolved limbs, an expected difference in F_A was not observed in COD trials. In this way, when landing and stabilization is quantified by knee F_A, involved limbs may mediate the landing and stabilization process, as governed by neuromuscular control, in a macroscale, movement trial-dependent manner as opposed to the consistent manner observed between SLD and COD trials of uninvolved limbs. This difference in F_A may indicate that the involved limb has adopted adverse landing techniques or has not completely reestablished healthy landing and stabilization mechanisms in comparison to the uninvolved limb for single leg tasks.

While the knee joint center did not display significant displacement asymmetries in the medial direction between involved and uninvolved limbs for any dynamic movement trial, the effective range of the joint during landing displayed asymmetric tendencies. The holistic evaluation of medio-lateral knee joint range provided a manner in which to control for inherent dynamic movement trial-specific differences that predispose knee displacement in the medial or lateral direction (consider SLD versus COD). Furthermore, the failure to observe significant medial knee excursions in involved limbs, commonly associated with a deficit of neuromuscular control, is notable. Significant asymmetries in the medio-lateral displacement of the knee joint center have been previously identified as adverse landing strategies for the ACL injured individuals (1). The supposition relating medial knee displacement and other limb asymmetries to deficits of neuromuscular control has been well characterized (24, 29, 38, 39, 40).

Damped Harmonic Oscillator Modeling of Medio-lateral Knee Movement: Fluency and Jolt

The clinical significance of medio-lateral knee F_A becomes particularly salient for the view of the knee, during landing, as a damped harmonic oscillator. Representative knee velocity versus time graphs, modeling SLD experimental data, depict this phenomenon in Figure 5:

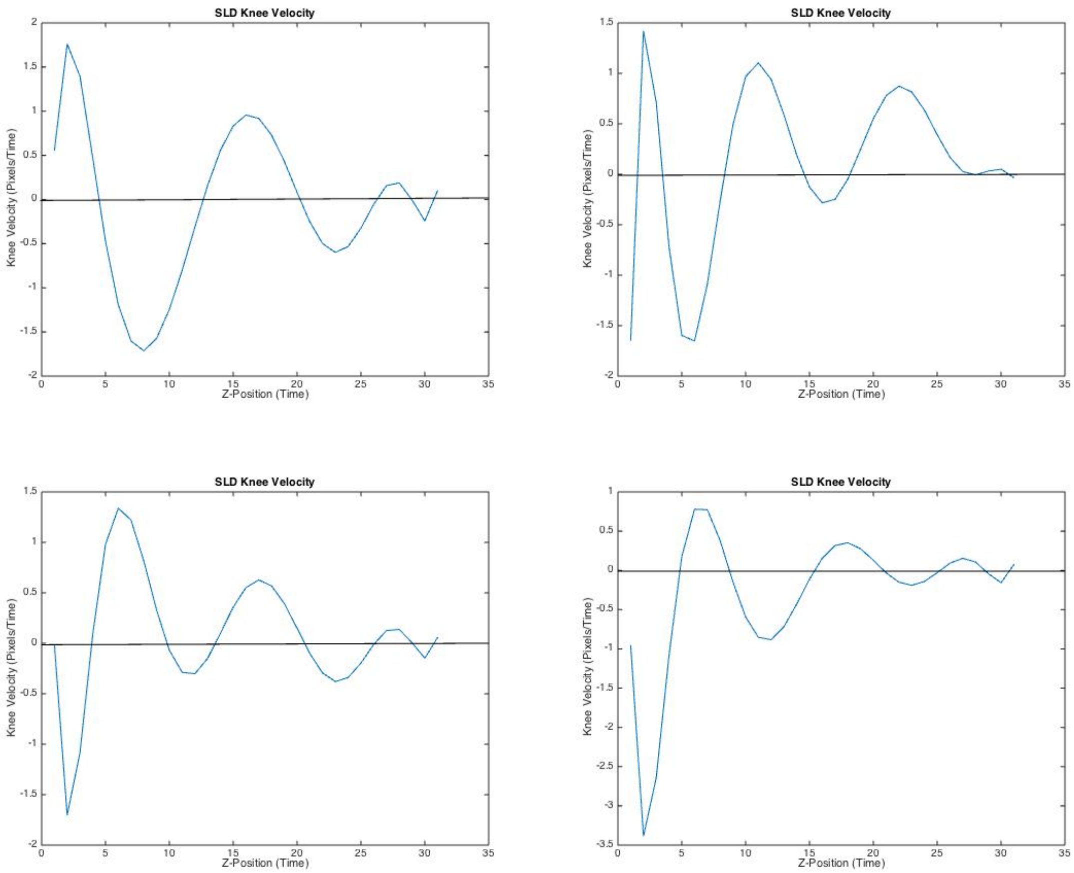

Figure 5. Representative Velocity-Time Curves Illustrating the Damped Harmonic Oscillator Pattern of Knee Deceleration During Dynamic Movement Tests

For a system with no extracorporeal factors acting on it, such as the knee during landing in SLD dynamic movement trials, the equilibrium force equation may be written as:

$$x'' + 2\zeta\omega_0 x' + \omega_0^2 x = F \quad \text{and} \quad \omega_0 = \sqrt{\frac{k}{m}} \tag{1}$$

Where ω_0 is the undamped angular frequency of the oscillator (the knee joint center), ζ is the damping ratio, F equals all external forces acting on the knee, and x is the position of the knee joint center. For knee fluency, the first derivative of position is the medio-lateral velocity of the knee joint center and is, consequently, the parameter that follows damped harmonic oscillation patterns. Taking the derivative of the above equation, with respect to x, when the sum of the external forces, F, equals zero, the equation becomes:

$$x''' + 2\zeta\omega_0 x'' + \omega_0^2 x' = 0 \qquad (2)$$

Where x''' represents jolt, the third derivative of position, x'' represents acceleration, and x' equals velocity of the knee joint center in the medio-lateral direction. The equation may be rearranged to solve for jolt:

$$x''' = -(2\zeta\omega_0 x'' + \omega_0^2 x') \qquad (3)$$

Because jolt is a vector and the forces derived from jolt are equally borne by the knee joint in the positive or negative direction of the 2D frontal plane, the absolute value of the jolt equation may be evaluated.

Focusing first on the $\omega_0^2 x'$ term, our results demonstrated insignificant differences in knee velocity between injured and uninjured limbs ($x'_{inv} = x'_{unv}$) throughout SLD trials. Furthermore, the number of fluent events experienced by the knee during landing may be equated to angular frequency for velocity versus time graphs and consequently serves relate fluency and ω_0. F_N was defined the number of fluent events per unit time; the inverse of this measure (F_A) was used to correlate larger numerical values to fluent movement. For SLD trials, F_A, or the inverse of the number was fluent events, was decreased for involved limbs. Taking the number of fluent events to be representative of the angular velocity, ω_0, the relationship between involved and uninvolved limbs may be established such that: $\omega_{0,inv} > \omega_{0,unv}$. Ultimately, it is determined that the relationship of the $\omega_0^2 x'$ term between involved and uninvolved limbs is:

$$[\omega_0^2 x']_{inv} > [\omega_0^2 x']_{unv} \tag{4}$$

Focusing next on the $2\zeta\omega_0 x''$ term, relations between involved and uninvolved knee accelerations may be derived. First, an increased number of fluent events for involved limbs compared with uninvolved limbs was observed. Coupled with the finding that the medio-lateral range of the knee was significantly reduced for the involved limb, without a significant difference in velocity between limbs for SLD trials, leads to the determination that the acceleration of the involved limb is greater than the uninvolved limb ($x''_{inv} > x''_{unv}$). The damping ratio, ζ, is a function of the damping coefficient, c, the spring constant of the oscillator, k, and the mass of the knee, m, where:

$$\zeta = \frac{c}{2\sqrt{m * k}} \tag{5}$$

While the mass and the spring constant of the knee are difficult to measure, the average damping coefficient may be determined experimentally. The average damping coefficient for SLD knee velocity versus time graphs, modeled as the rate of oscillatory decay, was not significantly different for involved and uninvolved limbs (involved: 0.2162±2.9678; uninvolved: 0.3141±2.3561; p = 0.8410), thus: $c_{inv} = c_{unv}$. To account for the immeasurable variables, a derivation may be performed to delineate the relationships for the $2\zeta\omega_0 x''$ term. Assuming equal masses between involved and uninvolved knees, the relationship for the $2\zeta\omega_0 x''$term may be established such that:

$$[2\zeta\omega_0 x'']_{inv} > [2\zeta\omega_0 x'']_{unv} \tag{6}$$

Finally, an analytical expression for jolt may be derived, using previously defined value relationships for the constituent terms, for involved and uninvolved limbs such that:

$$x''' = 2\zeta\omega_{0,inv} x''_{inv} + \omega_{0,inv}^2 x'_{inv} > 2\zeta\omega_{0,unv} x''_{unv} + \omega_{0,unv}^2 x'_{unv} \tag{7}$$

In this manner, the involved limb not only experiences more force (as a result of greater accelerations), but also generates a greater internal jolt than the uninvolved limb during the landing phase of SLD dynamic movement trials.

In a recent review of the mathematical relationship between jolt and musculoskeletal injury, Ivancevic (2009) showed that a damaging Euclidean jolt can occur when the entire body mass is supported with a semi-flexed knee, such as throughout the landing phase of SLD and COD trials analyzed in this study. A Euclidean jolt of sufficient magnitude possesses the injurious potential in this position particularly because, in a semi-flexed state, the knee maintains all 6 degrees of freedom of the joint. Consequently, a critical Euclidean jolt affects all 6 degrees of freedom simultaneously, with the ability to cause both soft and hard tissue damage depending on the intensity of the jolt. Similarly, the majority of ACL injuries occur through a non-contact mechanism during landing tasks that occur in conjunction with enhanced knee loads (17, 18). In this manner, the above relationship between several constituents of knee fluency in generating enhanced knee jolt for involved limbs under non-contact ($F_{external}=0$) scenarios is compelling when considered under previously characterized musculoskeletal (36) and ACL-specific, non-contact injury mechanisms (17, 18).

Conceptually, jolt, as a descriptor of how evenly an object accelerates or decelerates, may be an insightful measurement for force dissipation within the knee during landing. Furthermore, our findings relating differences in observed fluency values and analytical jolt relationships is significant in contributing to well-established evidence in ACL-injured individuals of incomplete recovering of healthy landing strategies (1), predisposition for associated morbidities such as osteoarthritis (36), and re-injury rates as high as 30% (37) and even further contextualizes and mathematically validates the clinical relevance of knee fluency values. In this manner, the validity of knee fluency, as a biomechanical descriptor of knee motion during landing, may be inherently vested in the mathematics of jolt. The experimental finding of diminished F_A values coupled with the analytical relation of greater jolt values generated by involved limbs makes knee fluency, and potentially jolt, clinically relevant as important preventative measures for athletes and as biomechanical parameters integral in rehabilitation assessments for ACL-injured athletes.

Implications for Neuromuscular Control

While a central tenet of the above observations is the absence of direct extracorporeal forces acting on the knee during landing, we further postulate that the damped oscillator model may inherently incorporate descriptors of neuromuscular control within the angular frequency variable, ω_0. Limb stabilization during landing requires balance achieved by the complimentary action of a host of muscles in the hip, thigh, and lower shank of the leg. The increase in the number of changes in velocity of the knee joint center of the involved limb (resulting in decreased fluency) could be a consequence of imprecision in the moments generated about the knee joint by these muscles. Contrasting this with the decreased amount of velocity changes of the knee joint center observed in the uninvolved limb (resulting in increased fluency) we propose that enhanced neuromuscular control in the uninvolved limb is responsible for the generation of more equivalent internal and external moments about the knee. With the resulting stabilization of the healthy limb characterized by a lesser amount of medio-lateral velocity changes (equally a diminished angular frequency value and demonstrating neuromuscular control), it logically follows that a deficit of neuromuscular control in the involved limb is an instability that manifests as a greater angular frequency.

CONCLUSION

2D frontal place knee motion, as an aspect of neuromuscular control, during dynamic movement trials is an important factor to assess in the rehabilitation process of ACL-injured athletes. Medio-lateral knee fluency has been identified as a novel indicator of knee stability during landing. This study is the first to describe differences in medio-lateral knee fluency for ACL-injured and uninjured limbs across SLD, COD, and DVJ dynamic movement trials. Our findings demonstrate significant inter-limb differences in medio-lateral knee control, directly supporting the notion of perturbed neuromuscular control after ACL injury and ACLR surgery. Furthermore, we have implemented a damped harmonic oscillator mathematical model of medio-lateral knee velocity during dynamic movement tests which relates knee fluency to jolt. Jolt is a measure of the uniformity of deceleration of the knee during landing and has been implicated in musculoskeletal injury. Further characterization the movement patterns demonstrated by healthy limbs during landing may provide new approaches for ACL-injury rehabilitation and endpoint determinations using biomechanical descriptors such as fluency and jolt.

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